8-2013

Comparison between LCOS projector and DLP projector in generating digital sinusoidal fringe patterns

Beiwen Li
Iowa State University, beiwen@iastate.edu

John Gibson
Bethune Cookman College

Jill Middendorf
Iowa State University

Yajun Wang
Iowa State University

Song Zhang
Iowa State University, song@iastate.edu

Comparison between LCOS projector and DLP projector in generating digital sinusoidal fringe patterns

Beiwen Li[1], John Gibson[2,*], Jill Middendorf[1], Yajun Wang[1] and Song Zhang[1+]

[1] Department of Mechanical Engineering, Iowa State University, Ames, IA, USA 50011.
[2] Department of Computer Engineering, Bethune-Cookman University, Daytona Beach, FL, USA 32114

ABSTRACT

Digital-light-processing (DLP) and liquid-crystal-on-silicon (LCOS) are two digital projection technologies which enjoy great popularity. This paper will demonstrate the performance of the two technologies in generating digital sinusoidal fringe patterns in the two following ways: focused-sinusoidal-patterns (FSP) method and defocused-binary-patterns (DBP) method. Experiment shows that for the FSP method, LCOS projector is a better choice since nonlinear gamma effect is less significant and there is no need for precise synchronization; While for the DBP method, DLP projector has the advantage over LCOS projector since the generated images have higher contrast ratio.

Keywords: digital light processing, liquid crystal on silicon, fringe analysis, binary defocusing, fringe projection

1. INTRODUCTION

In recent years, there has been an upsurge in the application of digital fringe projection (DFP) techniques owing to its speed, accuracy and flexibility.[1,2] The key to the success of the DFP technique is the capability of generating high-quality sinusoidal fringe patterns. Basically, there are two approaches to generate digital sinusoidal fringe patterns. Traditionally, sinusoidal fringe patterns are directly supplied to a focused video projector, which is called focused-sinusoidal-pattern (FSP) method. However, this technique was found to have the projector nonlinear gamma effect, and the rigid requirement of synchronization between projector and camera, which impedes the accuracy of measurement. Although a variety of gamma correction methods has been introduced and applied successfully,[3–8] none of those techniques are easy to implement. Furthermore, the gamma actually changes over time,[9] making this problem even more complex. In addition, the measurement speed is typically limited to 120 Hz.[10] Recently, Lei and Zhang has proposed a defocused-binary-pattern (DBP) method[11] that is to generate digital sinusoidal fringe patterns by properly defocusing squared binary patterns (SBP). This technology has the merit of: (1) avoiding the nonlinear gamma problem since only two grayscale values are used; (2) overcoming the speed limit of FSP method since the data transferring rate is greatly reduced; and (3) making synchronization between the camera and the projector not necessary.

The aforementioned statements regarding FSP and DBP method can well stand in general, but may subject to different kinds of projection technologies. Digital-light-processing (DLP) and liquid-crystal-on-silicon (LCOS) are two widely used digital projection technologies which have drawn great attention from researchers. They have different ways to generate grayscales. For the DLP technology, it works with the digital light processing technique using a digital micro mirror device (DMD) that generate different grayscale values by time integration.[12] It has been demonstrated its success in implementing in 3D shape measurement systems.[13–16] However, the problem associated with the FSP method cannot be overcome due to the time integration nature of its grayscale generation mechanism. LCOS is a another technology that has also been extensively studied for optical metrology.[17–19] For LCOS technology, it works with liquid crystals instead of individual mirrors. Compared with the sharp edges of micro-mirrors in a DLP system, the working mechanism of LCOS tends to bring smoother pixel edges,[20] and this property might alleviate the problems associated with FSP method. In this research, we will demonstrate that: (1) For the FSP method, the LCOS projector has the advantage over the DLP projector, since it has comparatively small nonlinear gamma effect and it is not sensitive to the exposure time used; (2) For the DBP method, a DLP projector is a better option since the smoother edges created by the LCOS projector would lower the contrast ratio of binary fringe stripes.

[*] This work was performed at Iowa State University when John Gibson was a summer research experience for undergraduate (REU) student.
[+] song@iastate.edu; phone 1 515 294 0723; fax 1 515 294 3261; www.vrac.iastate.edu/˜song.

Dimensional Optical Metrology and Inspection for Practical Applications II, edited by Kevin G. Harding, Peisen S. Huang, Toru Yoshizawa, Proc. of SPIE Vol. 8839, 883908 · © 2013 SPIE
CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2022225

Section 2 explains the principles of DLP and LCOS technologies. Section 3 shows comparing experimental results under different conditions for these two different projection technologies. Section 4 summarizes this paper.

2. PRINCIPLE

2.1 Fundamentals of DLP and LCOS technologies

DLP and LCOS are two widely applied fringe projection technologies. For the DLP projector, it produces grayscale value by time integration.[12] In detail, it works with a digital micro mirror device (DMD) that modulates the image pixel grayscale values by tilting the mirrors either into or away from the optical path. For a LCOS projector, it works with liquid crystals instead of individual mirrors. In LCOS, liquid crystals are applied to a reflective mirror substrate. As the liquid crystals open and close, the light is either reflected from the mirror below, or blocked. This modulates the light and creates the image. Comparing the working principles of the two technologies, it is indicated that DLP responds in a digital way since micro-mirrors would add high frequencies, what's more, the time integration might bring false output when there is an input grayscale other than 0 or 255. Whereas for LCOS technology, the nature of liquid crystals gives the analog-like responses, and thus smoother pixel edges and more stable grayscale output are created.[20]

In order to evaluate the effect that these two different techniques of generating grayscales have on projector output, a simple test was carried out for both projectors. A photodiode sensor (Thorlabs FDS100) was used to detect the output light and the photoelectric current signal was converted into voltage signal and monitored by an oscilloscope. A detailed description of the test system can be found in Section 3. Figures 1 and 2 show the result when uniform images are applied to both projectors. In order to simplify the test, only green channel is used. These experimental results showed that for the DLP projector, when it is fed with a pure green image (RGB = (0, 255, 0)), the channel is filled by almost 100%. When the grayscale value is reduced to 128 and 64 respectively, it generates irregular output; While for the LCOS projector, it can generate relatively stable output regardless of the grayscale values supplied. In this case, if a sinusoidal fringe pattern with grayscales varying from 0 to 255 is supplied, synchronization problem becomes significant for the DLP projectors, while it is a minor issue for the LCOS projector.

2.2 Three-step phase-shifting algorithm

A simple three-step phase-shifting algorithm with a phase shift of $2\pi/3$ was used in order to examine the effects that FSP and DBP method have on both projectors. Here, three projected fringes can be mathematically represented as

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi - 2\pi/3], \tag{1}$$

$$I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi], \tag{2}$$

$$I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi + 2\pi/3]. \tag{3}$$

Where $I'(x,y)$ indicates the average intensity, $I''(x,y)$ stands for intensity modulation, and $\phi(x,y)$ represents the phase to be solved for. The phase can be retrieved by simultaneously solving the equations (1)-(3):

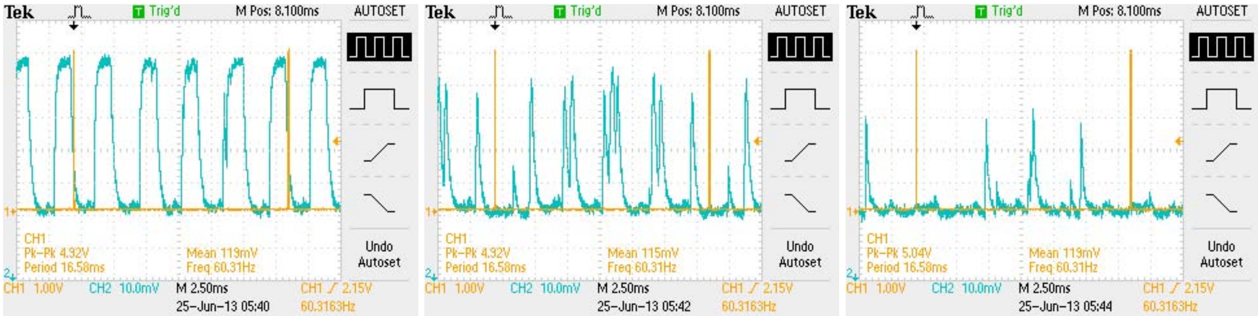
$$\phi(x,y) = \tan^{-1}\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3}. \tag{4}$$

Due to the nature of arctangent function, the phase is wrapped with a range from $-\pi$ to π. In order to obtain a continuous phase map, a phase unwrapping algorithm is needed to detect and remove 2π discontinuities by adding or subtracting integer multiples of 2π .[21]

3. EXPERIMENTS

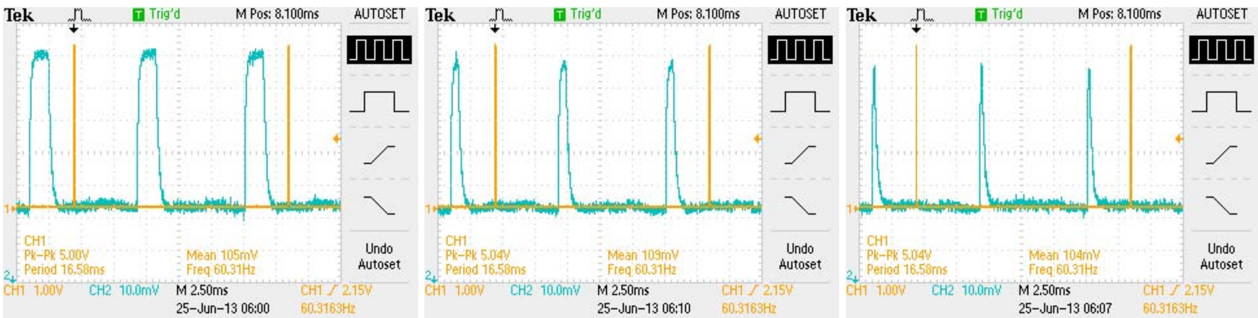
3.1 Test system

A test system was developed to perform the various tests. The system includes a DLP Dell projector (Model: M109S), a LCOS Oculon projector (Model: PP920), and a digital camera (Model: Jai Pulnix TM-6740CL). The DLP projector has a resolution of 800×600 with a projection distance of 0.6-2.4 m and a lens of $F/2.0$, f = 16.67 mm. The DMD used in the DLP projector is 0.45-inch Type Y chip. The LCOS projector has a resolution of 640×480 with a projection distance of 0.5-1.5 m. The camera uses a 16 mm focal length Mega-pixel lens (Model: Computer M1614-MP) at F/1.4 to 16C. The camera resolution is 640×480 with a maximum frame rate of 200 frames/sec. The camera pixel size is $7.4 \times 7.4\ \mu m^2$.



(a) (b) (c)

Figure 1: Example of the projected timing signal if the DLP projector is fed with a uniform greed image with different grayscale values. (a) Green = 255; (b) Green = 128; (c) Green = 64.

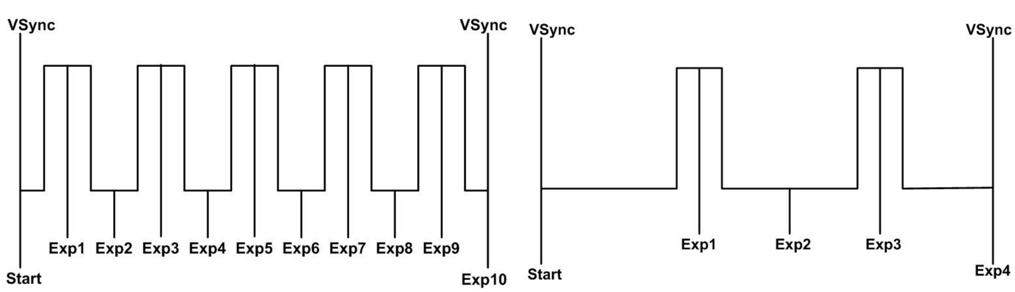


(a) (b) (c)

Figure 2: Example of the projected timing signal if the LCOS projector is fed with a uniform greed image with different grayscale values. (a) Green = 255; (b) Green = 128; (c) Green = 64.

3.2 Timing of both projectors

As is mentioned above in Section 2.1, the principles as to how LCOS projector and DLP projector generate grayscales are different. Figures 1 and 2 clearly illustrate the timing of LCOS projector and DLP projector, respectively. These figures also show that the DLP projector generates five pulses in a 1/60 sec projection cycle, while LCOS only generates two pulses in a 1/60 sec projection cycle. In this experiment, the camera exposure starts with the projector's VSync signal and ends either on a pulse or off a pulse.[22] The 10 exposure times taken for the DLP data acquisition are 2.50, 4.17, 5.83, 7.50, 9.17, 10.83, 12.50, 14.17, 15.80, and 16.67 ms as is illustrated in Fig. 3(a). Since the LCOS system only has two pulses in one cycle, only four exposure times were used (5.53, 8.33, 13.86, and 16.67 ms) as is shown in Fig. 3(b).



(a) (b)

Figure 3: Timing chart of camera exposures relative to the projection. All exposures start with the VSync signal and stop at different timings shown on the figure. (a) DLP system: Exp 1, Exp 2,..., and Exp 10 correspond to exposure time of 2.50, 4.17, 5.83, 7.50, 9.17, 10.83, 12.50, 14.17, 15.80, and 16.67 ms; (b) LCOS system: Exp 1, Exp2, Exp 3, and Exp 4 correspond to exposure time of 5.53, 8.33, 13.86, and 16.67 ms.

3.3 Projector nonlinear gamma

For the FSP method, the projector nonlinear gamma correction plays an important role since video projectors are designed to have nonlinear response to accommodate human vision. However, the projector's gamma varies from one projector to another and from one manufacturer to another even for the same technology (i.e., DLP or LCOS). We experimentally verified the difference between the LCOS projector and the DLP projector we used. Figure 4 shows the nonlinear gamma curve of the DLP and LCOS projector, This figure clearly shows that the gamma nonlinearity of the LCOS projector is not as significant as the DLP projector, indicating that the LCOS projector has better quality of measurement without gamma correction. In the following experiment, both DLP projector and LCOS projector are tested by measuring a uniform white flat board when the FSP method is applied without gamma correction. To eliminate issue associated with synchronization (to be demonstrated next), we used an exposure time of 16.67 ms to capture the whole projection cycle. Figure 5 shows the fringe patterns captured by the two projectors without gamma correction and their associated phase error. The phase error here was determined by comparing the phase obtained from three phase-shifted fringe patterns without gamma correction with a three-step phase-shifting algorithm with the ideal phase obtained by using ideal sinusoidal fringe patterns with gamma corrections. These experimental results confirmed that the LCOS projector had smaller phase error than DLP projector.

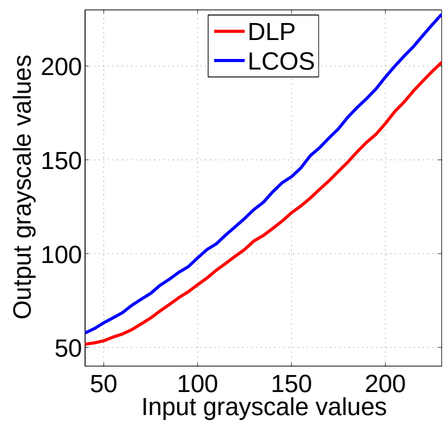


Figure 4: Nonlinear gamma effect of the LCOS and DLP projectors.

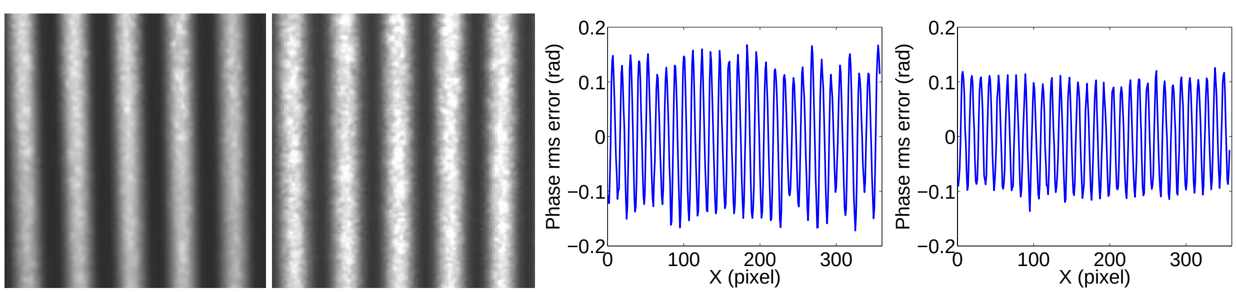
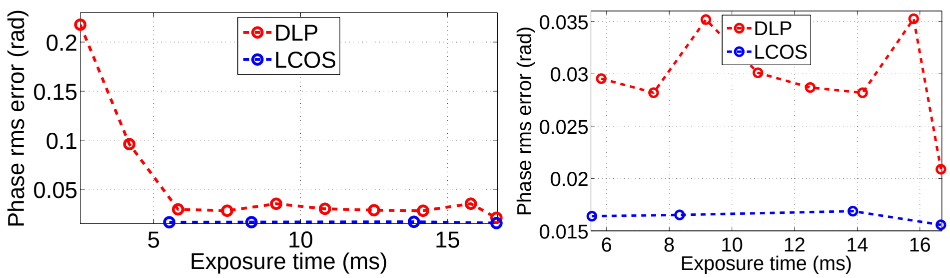


Figure 5: Comparing results of the DLP and LCOS system without gamma correction. (a) One of three phase-shifted fringe patterns using the DLP projector; (b) One of three phase-shifted fringe patterns using the LCOS projector; (c) One cross section of the phase error map from the patterns projected by the DLP projector (root-mean-squared (rms) error: 0.100 rad); (d) One cross section of the phase error map from the patterns projected by the DLP projector (rms error: 0.074 rad).

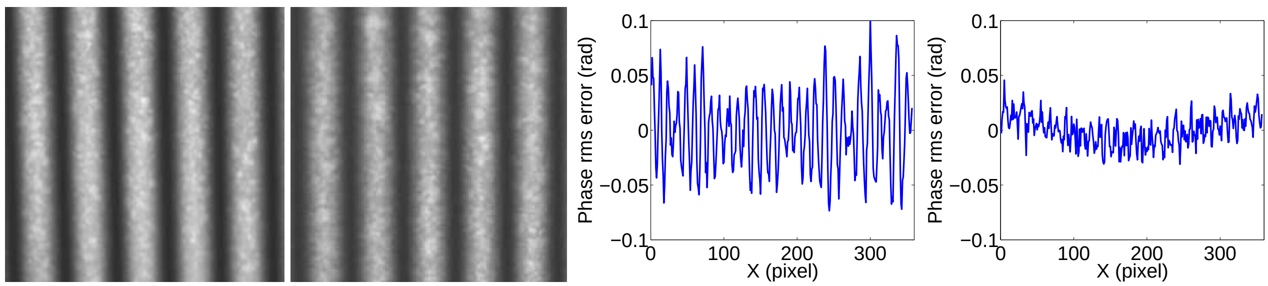
3.4 FSP method with different exposure times

To examine the difference when FSP method is applied to both projectors, we measured the same flat whiteboard with the change of exposure times as illustrated in Fig. 3. Figure 6 shows the results. It is important to note that for the following experiments presented in this subsection, the fringe period that we use is T = 18 pixels, and the nonlinear gamma effect has been corrected for both projectors using the approach discussed in.[7] Figure 6(a) shows the results, from which one can see that for DLP projector, when the exposure time is very short (2.50 ms and 4.17 ms), it cannot generate reasonable good-quality phase as the phase rms error is very large. Therefore, to better visualize the difference, Fig. 6(b) shows a zoomed-in plot that only depicts the result when the exposure time is longer than 5 ms. These experimental results indicate that for the DLP projector, the phase quality fluctuates if a different exposure time is used. Specifically, the phase error is smaller when the camera exposure ends off a pulse than that when the camera exposure ends on a pulse. This is mainly because when the camera exposure ends on a pulse, it may not capture the correct grayscale value due to the nature of DLP projection mechanism. In contrast, for the LCOS projector, the change of camera exposure does not have significant effect on phase quality. Figure 7 shows on typical results when the the camera exposure ends on a pulse for both projectors (15.80 ms for the DLP projector and 13.86 ms for the LCOS projector). It is obvious that the DLP projector has significantly larger phase error (approximately double) than the LCOS projector.



(a) (b)

Figure 6: Comparison between LCOS and DLP projectors with the FSP method using different exposure times. (a) Phase rms error for all exposure times; (b) zoomed-in view of (a) for exposure time between 5.53 ms and 16.67 ms



(a) (b) (c) (d)

Figure 7: Flat board measurement results using the FSP method when the camera exposure ends on pulse. (a) One of the captured fringe pattern projected by the DLP projector using an exposure time of 15.80 ms; (b) One of the captured fringe pattern projected by the LCOS projector using an exposure time of 13.86 ms; (c) One cross section of the phase error map from the patterns projected by the DLP projector (root-mean-squared (rms) error: 0.035 rad); (d) One cross section of the phase error map from the patterns projected by the LCOS projector (rms error: 0.017 rad).

A more complex 3D sculpture was also measured using the FSP method under the same circumstance as Fig. 7. Figure 8 shows the results. From the 3D results, we find that LCOS projector can provide measurement with higher quality than DLP projector (the vertical stripes are less obvious). The temporal phase unwrapping algorithm that we used was introduced in,[23] and the phase-to-height conversion method was introduced in.[24]

3.5 DBP method with different exposure times

Similarly, experiments are also carried out to examine the difference between DLP and LCOS projectors with the DBP method. Figure 9 shows the results of measuring a flat white board. This figure indicates that for both projectors, exposure time does not have significant impact on measuring quality, albeit the shorter exposure time tends to have larger phase rms error due to low signal to noise ratio of the captured fringe pattern. This is because for the DBP method, only two grayscale values (0 and 255) are used, both projectors can generate stable output as is shown in Fig. 1 and 2. Therefore, synchronization is not a major issue for either projector if the DBP method is used. Here, one may also notice that in

(a) (b) (c) (d)

Figure 8: Complex 3D statue measurement results using the FSP method when the camera exposure ends on pulse.. (a) One of the fringe patterns using the DLP projector with camera's exposure time of 15.80 ms; (b) One of the fringe patterns using the LCOS projector with camera's exposure time of 13.86 ms; (c) Corresponding reconstructed 3D results of (a); (d) Corresponding reconstructed 3D results of (b).

general, the LCOS projector results slightly larger phase error than the DLP projector does. Figure 10 shows the captured fringe patterns and the associated phase error. Figures 10(a) and 10(b) clearly show that the fringe pattern projected by the DLP projector has higher contrast than the LCOS projector, resulting in better signal to noise ratio and less random phase errors as illustrated in Figs. 10(c) and 10(d). It is important to note that for this experiment, the camera was synchronized with both projectors and the exposure time was 16.67 ms to avoid issues related to synchronization.

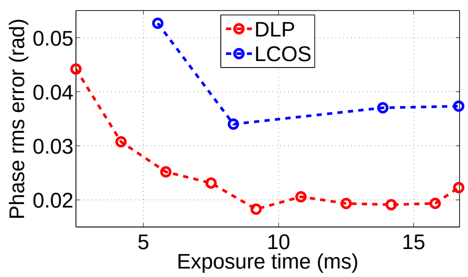
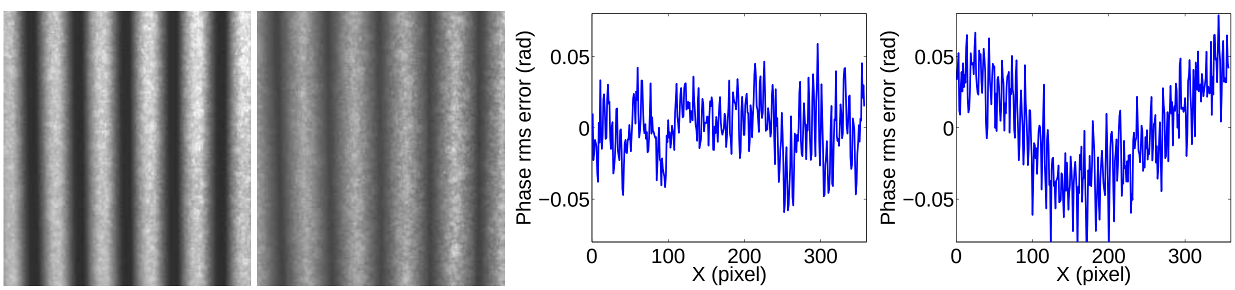


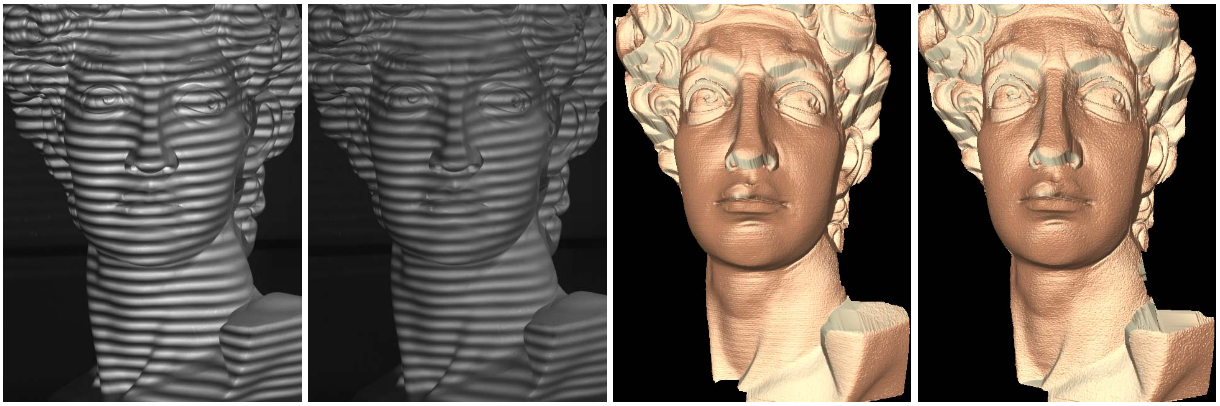
Figure 9: Comparison between LCOS and DLP projectors with DBP method.



(a) (b) (c) (d)

Figure 10: Flat board measurement results using the DBP method when the camera is synchronized with the projector. (a) One of the fringe patterns with the projector DLP projector; (b) One of the fringe patterns with the projector LCOS projector; (c) One cross section of the phase error map from the patterns projected by the DLP projector (rms error: 0.022 rad); (d) One cross section of the phase error map from the patterns projected by the LCOS projector (rms error: 0.037 rad).

Similarly, a more complex 3D sculpture was also measured by the DBP method with the camera and projector being synchronized. Figure 11 shows the captured fringes and the corresponding recovered 3D shape. From the 3D results, we find that both projectors can provide high-quality 3D shape measurement results with the DBP method, but LCOS projector has a slightly lower measurement quality. This is again because the LCOS projector has lower contrast ratio than the DLP projector.



(a) (b) (c) (d)

Figure 11: Complex 3D object measurement results using the DBP method when the camera is synchronized with the projector. (a) One of the fringe patterns with the projector DLP projector; (b) One of the fringe patterns with the projector LCOS projector; (c) Corresponding reconstructed 3D results of (a); (d) Corresponding reconstructed 3D results of (b).

4. CONCLUSIONS

This paper has compared the performance of a DLP projector and a LCOS projector for high-quality 3D shape measurement. Due to their fundamental difference on grayscale image generation, we found that for the FSP method, the LCOS projector performs better than the DLP projector since no precise synchronization between the projector and the camera is necessary; and when no nonlinear gamma correction is used, the LCOS projector also has better performance than DLP projector because its gamma is close to be linear for the particular LCOS projector we experimented. However, for the DBP method, the DLP projector proves to be a better option since its fringe contrast is higher, making it higher signal to noise ratio and thus smaller random phase error.

REFERENCES

[1] Geng, J., "Structured-light 3d surface imaging: a tutorial," *Advances in Opt. and Photonics* **3**(2), 128–160 (2011).

[2] Gorthi, S. and Rastogi, P., "Fringe projection techniques: Whither we are?," *Opt. Laser. Eng.* **48**, 133–140 (2010).

[3] Kakunai, S., Sakamoto, T., and Iwata, K., "Profile measurement taken with liquid-crystal grating," *Appl. Opt.* **38**(13), 2824–2828 (1999).

[4] Guo, H., He, H., and Chen, M., "Gamma correction for digital fringe projection profilometry," *Appl. Opt.* **43**, 2906–2914 (2004).

[5] Pan, B., Kemao, Q., Huang, L., and Asundi, A., "Phase error analysis and compensation for nonsinusoidal waveforms in phase-shifting digital fringe projection profilometry," *Opt. Lett.* **34**(4), 2906–2914 (2009).

[6] Huang, P. S., Zhang, C., and Chiang, F.-P., "High-speed 3-d shape measurement based on digital fringe projection," *Opt. Eng.* **42**(1), 163–168 (2002).

[7] Zhang, S. and Huang, P. S., "Phase error compensation for a three-dimensional shape measurement system based on the phase shifting method," *Opt. Eng.* **46**(6), 063601 (2007).

[8] Zhang, S. and Yau, S.-T., "Generic nonsinusoidal phase error correction for three-dimensional shape measurement using a digital video projector," *Appl. Opt.* **46**(1), 36–43 (2007).

[9] Zhang, S., "Recent progresses on real-time 3-d shape measurement using digital fringe projection techniques," *Opt. Laser Eng.* **48**(2), 149–158 (2010).

[10] Gong, Y. and Zhang, S., "Ultrafast 3-d shape measurement with an off-the-shelf dlp projector," *Opt. Express* **18**(19), 19743–19754 (2010).

[11] Lei, S. and Zhang, S., "Flexible 3-d shape measurement using projector defocusing," *Opt. Lett.* **34**(20), 3080–3082 (2009).

[12] Hornbeck, L. J., "Digital light processing for high-brightness, high-resolution applications," in [*Proc. SPIE*], **3013**, 27–40 (1997).

[13] Geng, J., "Dlp-based structured light 3d imaging technologies and applications," in [*Proc. SPIE*], **7932**, 79320B (2011).

[14] Frankowski, G. and Hainich, R., "Dlp-based 3d metrology by structured light or projected fringe technology for life sciences and industrial metrology," in [*Proc. SPIE*], **7210**, 72100C (2009).

[15] Hfling, R. and Aswendt, P., "Real-time 3d shape recording by dlp-based all-digital surface encoding," in [*Proc. SPIE*], **7210**, 72100E (2009).

[16] Zhang, S. and Huang, P., "High-resolution, real-time 3-d shape acquisition," in [*IEEE Comp. Vis. and Patt. Recogn. Workshop*], **3**, 28–37 (2004).

[17] Schwab, X., Kohler, C., Krner, K., Eichhorn, N., and Osten, W., "Improved micro topography measurement by lcos-based fringe projection and z-stitching," in [*Proc. SPIE*], **6995**, 69950Q (2008).

[18] Riehemann, S., Palme, M., Kuehmstedt, P., and Notni, G., "P-15: Lcos based projection systems for optical metrology," *SID Symposium Digest of Technical Papers* **34**(1), 256 – 259 (2003).

[19] Michalkiewicz, A., Kujawinska, M., Krezel, J., Salbut, L., Wang, X., and Bos, P. J., "Phase manipulation and optoelectronic reconstruction of digital holograms by means of lcos spatial light modulator," in [*Proc. SPIE*], **5776** (2005).

[20] Powell, E., "What's so hot about lcos technology?," (2003).

[21] Ghiglia, D. C. and Pritt, M. D., [*Two-Dimensional Phase Unwrapping: Theory, Algorithms, and Software*], John Wiley and Sons, Inc, New York, NY (1998).

[22] Lei, S. and Zhang, S., "Digital sinusoidal fringe generation: defocusing binary patterns vs focusing sinusoidal patterns," *Opt. Laser Eng.* **48**(5), 561–569 (2010).

[23] Wang, Y. and Zhang, S., "Superfast multifrequency phase-shifting technique with optimal pulse width modulation," *Opt. Express* **19**(6), 5143–5148 (2011).

[24] Xu, Y., Ekstrand, L., Dai, J., and Zhang, S., "Phase error compensation for three-dimensional shape measurement with projector defocusing," *Appl. Opt.* **50**(17), 2572–2581 (2011).